Earth Surface Processes and Landforms
Earth Surf. Process. Landforms **23**, 481–492 (1998)

GRANULOMETRIC STUDY OF THE HANAUPAH FAN, DEATH VALLEY, CALIFORNIA

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Received 18 August 1997; Revised 23 February 1998; Accepted 23 February 1998

ABSTRACT

We applied new granulometric techniques to the various surfaces of the Hanaupah Fan, Death Valley, California, namely the Q1 surface, with an estimated age of 800–490 ka, the younger Q2 (170–105 ka) and Q3 (50–14 ka) surfaces, the <14 ka deposits of the incised channel, and to a (*c*. 14 ka) Lake Manly shoreline deposit at the northern periphery of the fan. We used these techniques to generate quantitative information on surface clast grain-size distributions, clast sphericity, roundness, and clast orientation to provide a data set that could be used to define fan-segment surfaces, and to help interpret fan genesis. Grain-size analyses were carried out by photo-sieving of 139 surface pictures, by petrographic identification of samples taken in the incised channel, and by identification and measuring of the largest clasts (1452 measurements) on the Q3 surface.

The results show that all fan-segment surfaces, regardless of age, have similar size distributions, with a well-defined gravel mode of −2·3 to −3·0 phi, and are poorly to moderately sorted. Samples from the incised channel have distributions that are very similar to each other, regardless of distance from the apex, but display reduced sorting compared to the fan surfaces (which largely lack fines, perhaps from winnowing by secondary overland flow). Only the shoreline deposit is different from the other elements, showing a much narrower, well-defined gravel mode (−3·0 phi), and is moderately well sorted. Sphericity and roundness of clasts on all surfaces show only minor differences, similar to the other sedimentary parameters, indicating a remarkable homogeneity of the surfaces of the sediment body. In addition, measurements of the largest clasts (>100 cm long axis) on the Q3 surface showed no discernible trend either with radial distance or with rock type. These data suggest large depositional episodes that produce extensive sedimentary units without differentiation relative to distance from the source.

Of the examined parameters, clast orientation is the best predictor of relative age of fan surfaces. Clast orientation in the main channel is bimodal, i.e. the long axes of clasts are either at right angles or parallel to transport direction. This bimodality disappears with increasing age, and the preferred orientation becomes unimodal (long clast axes normal to transport direction) on the Q1 surface. Although the causes of this change are still in debate, use of this parameter as a relative-age dating tool seems possible. © 1998 John Wiley & Sons, Ltd.

KEY WORDS: alluvial fan; debris flow; granulometric techniques.

INTRODUCTION

The spectacular alluvial fans of Death Valley, California (Figure 1), and surrounding areas, have been the subject of study and debate for several decades (e.g. Lustig, 1965; Denny, 1965; Hooke, 1972; Dorn *et al*., 1987a; Dorn, 1988, 1989; Hooke and Dorn, 1992). One of the best known of these fans is the Hanaupah Canyon Fan, on the west side of the valley (Figure 1 and 2), and readily accessible by a jeep trail from the West Side Road. This fan has been the subject of considerable controversy, particularly with respect to specific mode of formation, and to age assignments of the various segment surfaces of the fan (Hooke, 1972; Dorn *et al*., 1987a, b, 1989; Wells and McFadden, 1987; Dorn, 1988, 1989; Hooke and Dorn, 1992; Blair and McPherson, 1994, and

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CCC 0197-9337/98/060481–12 $17.50

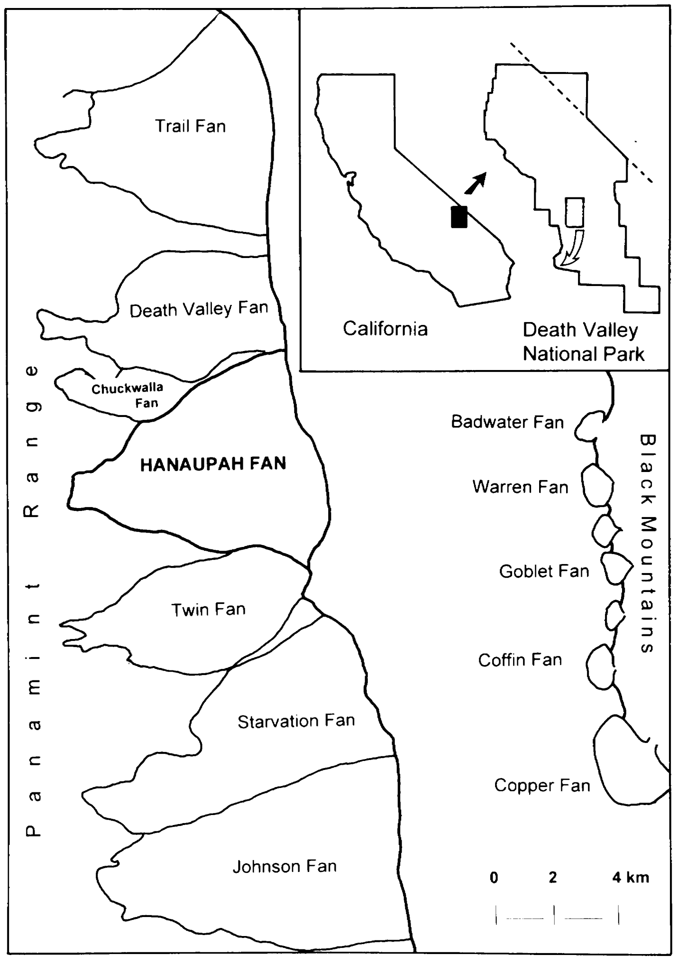

Figure 1. Index map

references therein). Included in this debate is the still unresolved controversy concerning climatic and tectonic influences on fan development.

Hanaupah Fan has been built primarily by debris flows, whose surfaces have been modified by fine-fraction winnowing from overland flows (Blair and McPherson, 1994). The fan contains a prominent incised channel that extends about 6 km below the fan apex to a fault scarp present in the toe of the fan (Figure 2). Individual fan surfaces (and their ages) mapped by Hooke (1968, 1972), and Hooke and Dorn (1992) are: Q1, 800–490 ka; Q2, 170–105 ka; and Q3, 50–14 ka (Figure 2). In addition, there is the recent, active incised channel and inactive parts of the incised channel leading to the active depositional lobe, features mapped as Q4 by Hooke and Dorn (1992). The various fan surfaces are readily distinguishable in the field and are characterized by increasingly (with age) better development of rock varnish, at least back to Q2, and by increasing dissection. The older Q1 and Q2 surfaces are preserved only on the south side of the incised channel, whereas the Q3 surface is present only on the north side of the channel. A model of the evolution of this fan system is presented by Dorn (1988) and Hooke and Dorn (1992).

Dorn (1988), Dorn *et al*. (1987a, 1989), and Hooke and Dorn (1992) used a variety of age-dating techniques, such as cation-ratio determinations of rock varnish, and ^{14}C dating (both conventional and AMS) of organic material trapped beneath the rock varnish, to establish the ages of the various surfaces given above. (Age determination based on cosmogenic nuclides was not employed.) These age assignments, however, were

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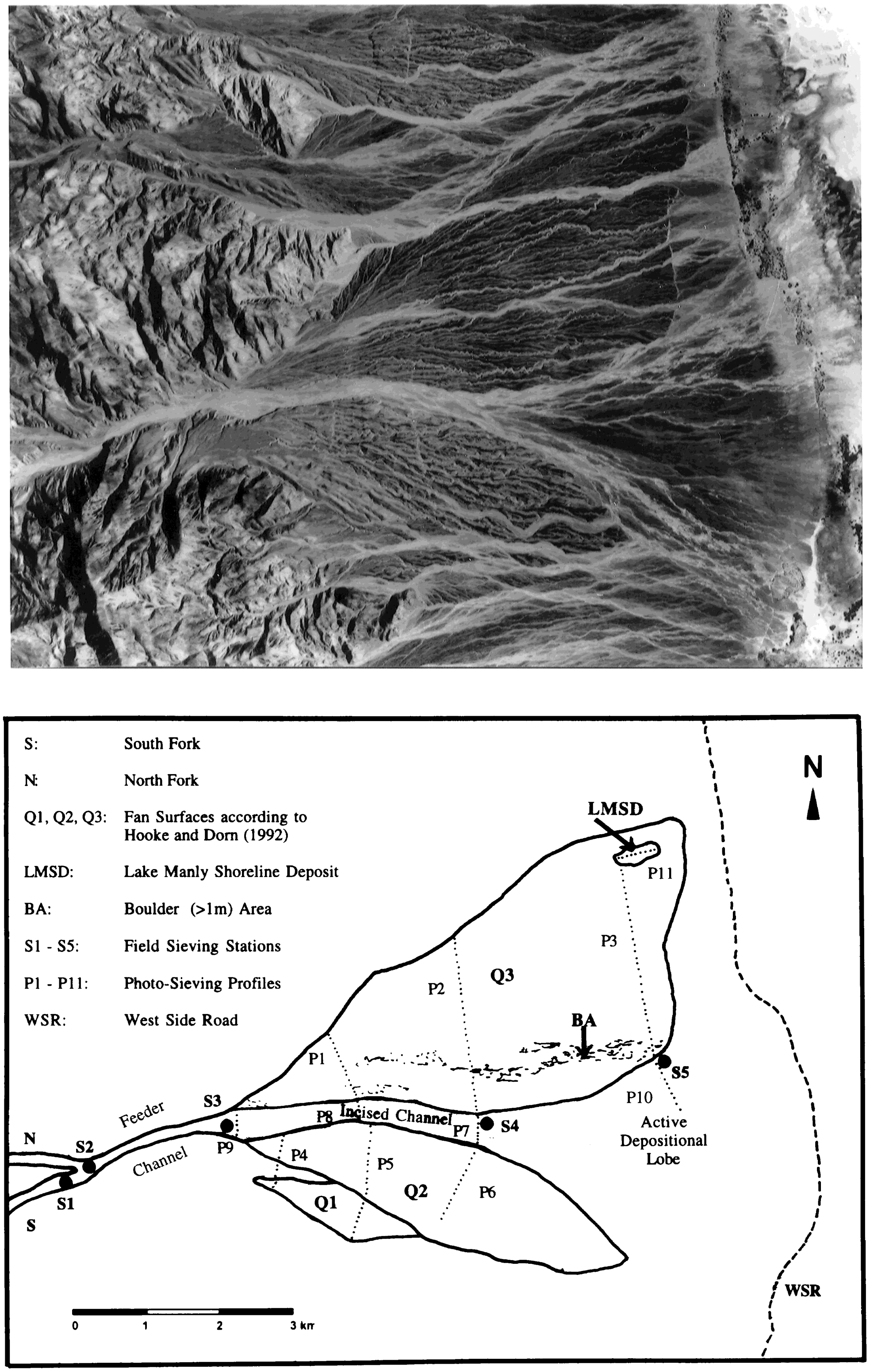


Figure 2. (A) Aerial photograph of Hanaupah Fan. (B) Index map of the Hanaupah Fan, including surfaces after Hooke and Dorn (1992), field-sieving stations, and photo-sieving profiles. Scale is the same for A and B

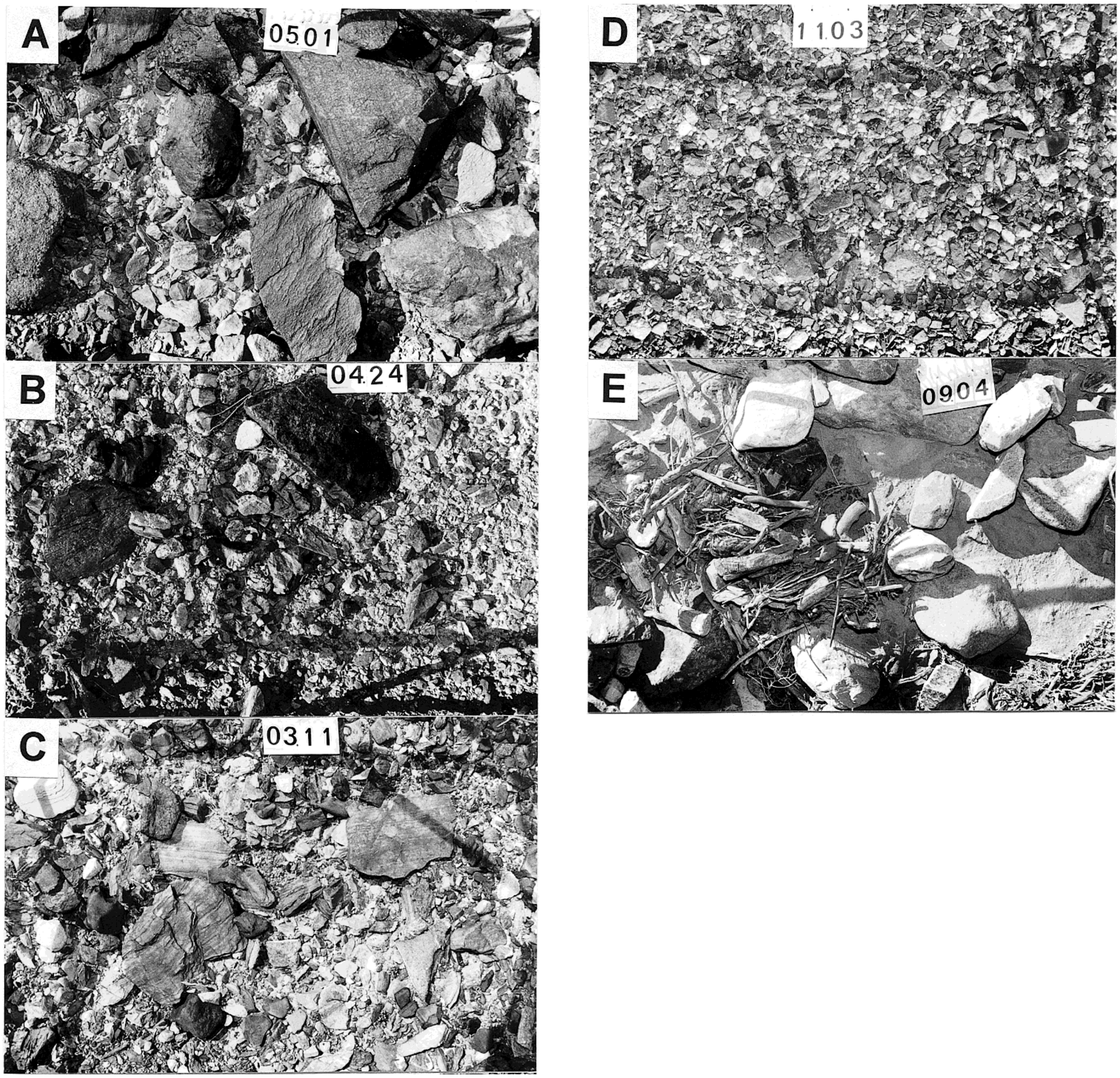


Figure 3. Examples of vertical photographs, covering an area of 1 x 1·5 m. The label on each photograph points towards the west, i.e. the apex of the fan. The samples represent a random selection of photographs; they are not typical of their respective profiles. Each profile has both finer and coarser parts (with the exception of Profile 11 across the Lake Manly shoreline deposit). The small differences between surfaces Q1, Q2, Q3 as well as the incised channel and the shoreline deposit, become apparent only by comparison of the statistical means of the combined profiles. The photographs include: (A) very coarse-grained surface on Q2; (B) coarse-grained surface on Q1; (C) coarse-grained surface on Q3; (D) relatively finer-grained surface on the Lake Manly shoreline deposit; and (E) surface in the incised channel

questioned by Wells and McFadden (1987), who doubted the possibility of using such methodologies to determine ages of fan surfaces. Additionally, Dorn *et al*. (1987a) and Dorn (1988, and references therein) used ^{13}C determinations, concentrated on individual layers of rock varnish, to determine climatic influences on fan development, and determined that fan aggradation occurred primarily during lengthy, humid periods in the Pleistocene, an interpretation that was questioned by Wells and McFadden (1987). Other models stressed the importance of climatic change on fan development, e.g. Reheis *et al*. (1996) who established that fan-building episodes occurred primarily during transitions from wetter to drier climatic conditions. On the other hand, the

postulated climatic influences on fan-building processes have been criticized, based on our inability to unequivocally ascribe certain fan-building processes to climatic influences (Blair, 1987; Blair and McPherson, 1994). Other workers considered the tectonic influences on the evolution of Hanaupah Fan (e.g. Hooke, 1972), while still others proposed combinations of these various elements.

Because of the interest in Hanaupah Fan, we decided to carry out a quantitative study of possible trends on the various fan surfaces with respect to grain-size distributions, clast sphericity, roundness and orientation, and to examine the dependence of these parameters on size and lithology of clasts. This type of information has not previously been presented. The purpose of our evaluation was to determine if such information could differentiate and characterize the various fan surfaces and other subenvironments, and whether or not such information would help in resolving some of the controversies indicated above. Most of the field work was carried out in March and October of 1989, followed by almost yearly visits for additional observations.

GRAIN-SIZE ANALYSES

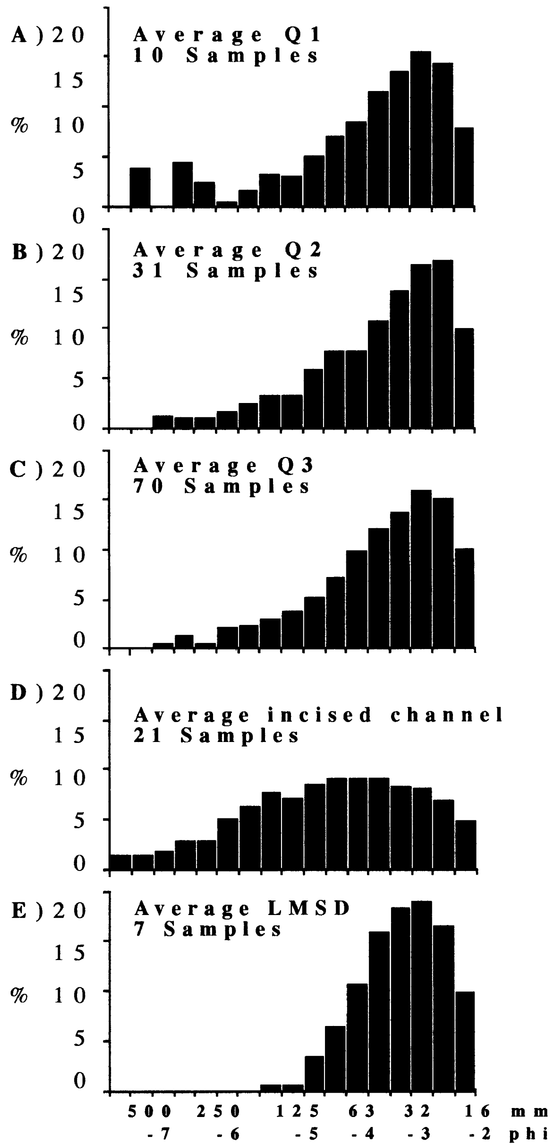
Methods

Grain-size analyses were carried out by means of photo-sieving, an optical method designed by Ibbeken and Schleyer (1988), and further developed by Diepenbroek *et al*. (1992). In this method, ‘vertical’, scaled photographs are taken from a distance of about 3 m above ground, with the camera attached to a movable frame. We took 325 oriented photographs along seven transects on the various fan segments, and on four transects in the incised channel (Figure 2). We selected 139 of these (each representing an area of 1 x 1·5 m) spaced 80 m apart, for further analysis (Figure 3). This study involved digitizing the outlines of about 900 clasts per photograph on a digitizing tablet, and computation of sedimentary parameters by Fourier analysis. The method not only yields the conventional parameters describing grain-size distributions, but also information on clast orientation relative to transport direction. It must be emphasized that this method only yields information on clast populations at the fan surface, and is limited by the resolution attainable on photographs (down to −2 phi. However, where the photographed surface is an active-channel floor, or the side wall of an incised channel, the results of photo-sieving and mechanical sieving are readily comparable (Ibbeken and Schleyer, 1988). The photo-sieving method is ideal for analysing fan surfaces; indeed it is the only realistic method of doing so since the alternatives would mean either (a) the complete removal of the surface-clast population, usually desert pavement, or (b) the measurement of about 900 clasts at each station in the field. The total number of digitized clasts in this study is about 125,100. No attempt was made to combine the results of photo-sieving with those of actual sieving in a single analysis.

A separate set of samples was collected in the incised channel, where disturbance of the natural surface was not a problem, and the 16–64 mm fractions were isolated by mechanical sieving for petrographic analysis.

Results

Three unique grain-size distributions are demonstrated by the results of the combined photo-sieving analyses, coincident with the samples from the surfaces, incised channel, and Lake Manly shoreline (Figure 4). All of the variously aged fan-segment surfaces have similar grain-size distribution, with a well-defined pebble mode (−2·3 to −3·0 phi). Although the photo-sieving methodology excludes sand-sized and finer fractions, field evidence shows that the fan surfaces are largely devoid of these finer fractions (Figure 3), despite the fact that these finer fractions account for about 30 per cent in the debris-flow deposits sampled in the incised channel wall, and subjected to mechanical sieving. It should be noted, however, that the desert pavement usually has a thickness of one clast only. If one of these surface clasts is removed, finer-grained material is abundant, supporting a winnowed origin. Maximal sizes seem to decrease slightly from Q1 to Q2 (Figure 4). Because the camera stand was positioned at distances of 80 m along a profile, regardless of the ‘roughness’ of the surface, this slight decrease may not be an artifact of the sampling method (i.e. noise). Still, this possibility cannot be excluded because the profile lines would have to be positioned ‘shoulder to shoulder’ to positively exclude any inadvertent bias. In any event, such a decrease in maximum size is not discernible on individual profiles on the large Q3 surface (Figure 5 D–F).



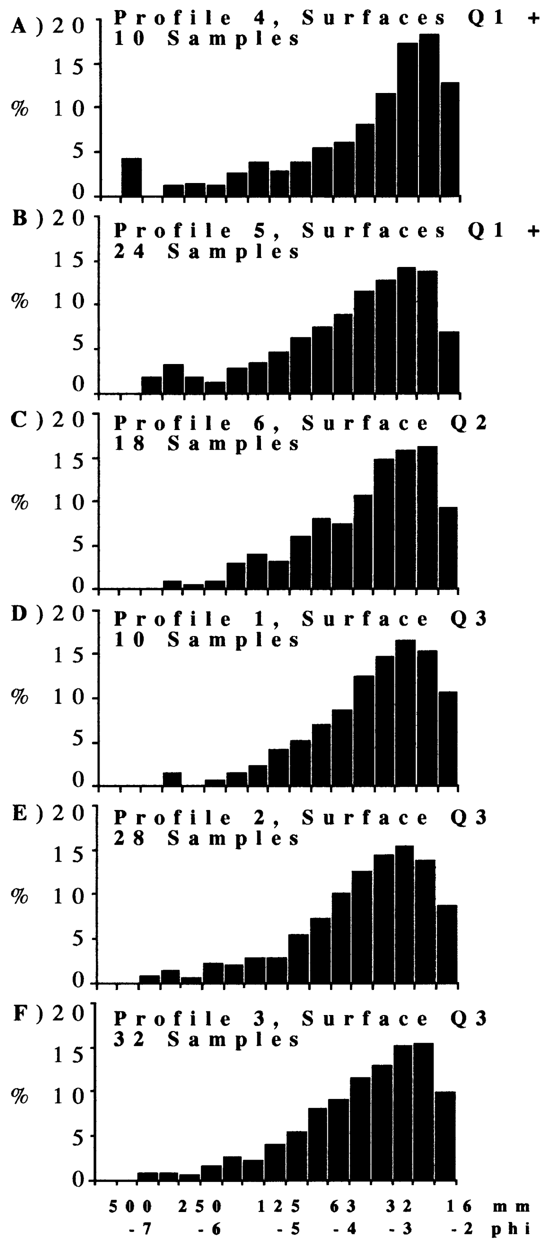


Figure 4. Comparison of averaged grain-size distributions (weight percentage) of profiles, including: (A) Q1; (B) Q2; (C) Q3; (D) the shoreline deposit (LMSD) and (E) the incised channel. Grain-size distributions for surfaces Q1 and the incised channel are poorly sorted (Q1:$\sigma_I = 1{\cdot}222\Phi$; incised channel: $\sigma_I = 1{\cdot}337\Phi$; inclusive standard deviation (after Folk and Ward, 1957) ; Q2 is moderately sorted ($\sigma_I = 0{\cdot}983\Phi$, and the shoreline deposit is moderately well sorted ($\sigma_I = 0{\cdot}629\Phi$). The largest clasts occur on Q1, and in the incised channel

Figure 5. Composite grain-size distributions (weight percentage) of individual profiles (P1 – P6 on Figure 2). Profiles 4 and 5 are poorly sorted ($\sigma_I = 1{\cdot}224\Phi$ resp. $\sigma_I = 1{\cdot}167\Phi$). Profiles 6 ($\sigma_I = 0{\cdot}943\Phi$), 1 ($\sigma_I = 0{\cdot}870\Phi$), 2 ($\sigma_I = 0{\cdot}989\Phi$) and 3 ($\sigma_I = 0{\cdot}976\Phi$) are moderately sorted. Note the overall similarity in grain-size distributions between these profiles

The incised channel has grain-size distributions which are nearly identical from the apex to the base, a distance of *c.* 6 km, and display significantly reduced sorting, compared to the fan surfaces (Figure 6). There is no decrease in maximum grain size with distance from the source. Indeed, the lower reach of the channel has clasts with maximum diameters of >5 m. Whether these large clasts are transported in the channel, or are eroded

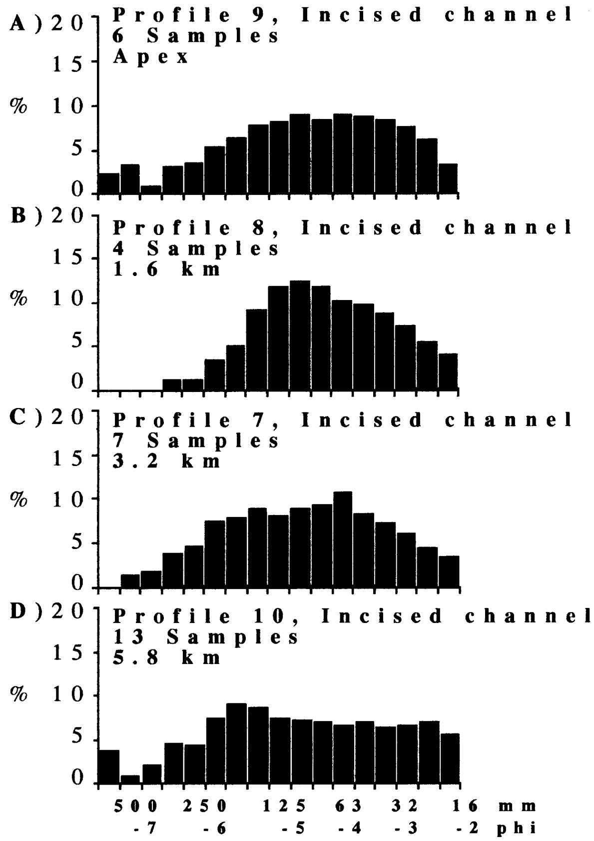


Figure 6. Composite grain-size distributions (weight percentage) of profiles in the main channel (refer to Figure 2 for location of profiles). The 'kilometre labels' on the plot refer to distance of profiles from the fan apex. All distributions are poorly sorted (P9: $\sigma_I = 1{\cdot}403\Phi$; P8: $\sigma_I = 1{\cdot}037\Phi$: P7: $\sigma_I = 1{\cdot}261\Phi$; P10: $\sigma_I = 1{\cdot}468\Phi$). The profiles show very little change downstream, including in maximum clast size

from the channel walls, cannot be ascertained. The shoreline deposit is different from the other deposits, having a much narrower, well-defined gravel mode (–3·0 phi), and is moderately well sorted.

DISTRIBUTION OF BOULDERS ON Q3

Methods

Boulders occur across the entire fan surface, but seem to be concentrated in elongate zones. In order to assay whether or not there is a systematic decrease in the size or rock type of boulders with respect to distance from the fan apex, a separate phase of investigations was carried out on a concentration of boulders that occurs in a band, about 4 km long, and a few hundred metres wide, north of the incised channel (Figure 2). Within this area, we measured a total of 1,452 clasts with long axes >100 cm, noting also their location, size and lithology.

Results

A composite grain-size distribution of these individually measured, large clasts is presented in Figure 7. The readily apparent asymmetry to the coarse side cannot be caused by the 'cutoff size' at 1·0 m, because the 1·0 – 1·20 m size interval is entirely missing from the distribution. It is perhaps a reflection of joint spacing in the granitic bedrock source area (see below). Grain-size distributions of clusters of these large clasts cannot be combined with grain-size distributions of other samples, regardless of the methodology employed (photo-sieving or actual sieving). It seems that the large clasts form a separate population, resulting from a complicated

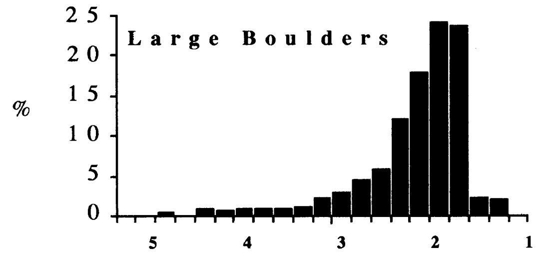


Figure 7. Composite grain-size distribution of large clasts on Q3, as determined by measurements of the long axes of 1,452 individual clasts. Size in metres

interaction between availability (mainly granite) in the source area, selection during transport, and specific transport mechanism, e.g. rolling, or rock-fall and continued rolling. With respect to composition of these individually measured, large clasts, granite is by far the dominant rock type (92·1 per cent), followed by quartzite (4·1 per cent), carbonates (2·4 per cent), and others (1·4 per cent). This composition is different from the lithologic composition of individual clasts in the incised channel, and also suggests that the large clasts on the Q3 surface may form a separate population. The occurrence of these large clasts on the fan surface shows no discernible trends, either with respect to size of individual clasts or rock type.

CLAST COMPOSITION

In addition to lithologic determinations of the large, individual clasts described above, we determined macroscopically the lithology of about 300 individual clasts in the 16–64 mm fractions of samples in the incised channel, separated by mechanical sieving (Figure 8). Composition of clasts embedded in the fan surfaces was not determined because of the ubiquitous presence of rock varnish.

We subdivided the clasts according to lithology as follows: argillite, siltstone and sandstone, largely derived from the Precambrian Pahrump Group; carbonate rock, derived from the upper Precambrian Noonday Dolomite; quartzite, derived from the upper Precambrian Stirling Quartzite; and granite, derived from the Miocene Little Chief Stock, which crops out only in the drainage basin of the south fork of Hanaupah Canyon. All lithologic assignments and ages of formations are based on Labotka *et al*. (1980) and Albee *et al*. (1981). Other rock types (which cannot be assigned a specific provenance) are amphibolite, diorite?, and other, macroscopically undeterminable rock types. Surprisingly, no clear differentiation with distance emerged, i.e. there is no selectivity of the transport mechanism with respect to rock type (see Figure 8). The small variability that exists can perhaps be explained by local factors, such as the relative enrichment of granite in sample S1, caused by the proximity of the Little Chief Stock (refer to the geologic map by Albee *et al*. (1981)).

CLAST SPHERICITY AND ROUNDNESS

Methods

Sphericity and roundness values are based on two sets of samples: (1) the photo-sieved samples from the fan surfaces, and (2) samples from the incised channel. The latter were selected by picking 300 clasts of argillite, and the same number of granite clasts, from the 16–40 mm size fractions of the samples used for identification of clast composition. The three projection planes of these clasts were photographed using a 16 mm camera in single-frame operation. Clast outlines on these photographs were digitized using a video camera and a computer with frame grabber. Fourier analyses of these digitized outlines yielded clast sphericity and roundness (see Diepenbroek *et al*. (1992) for description of the development of analytical techniques, and description of the necessary hardware and software).

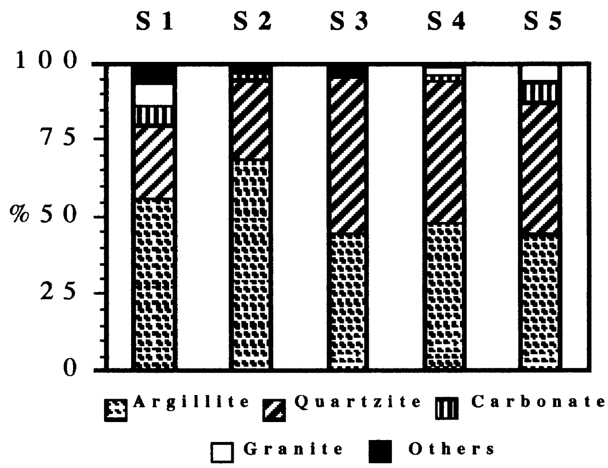


Figure 8. Petrographic composition of clasts in the 16 – 64 mm fraction of samples S1 – S5 (mechanical sieving, refer to Figure 2 for locations) in number percentage. S1 is in the south fork of the feeder channel, and is the point of origin of the distance-measuring system. S2 at 350 m shows the addition of argillites from the North Fork. S3 is at the apex of the incised channel at 1390 m. S4 and S5 are at 5420 m and 7970 m, respectively. Between samples S3 and S5, over a distance of 6·03 km, there is no significant change in petrographic composition

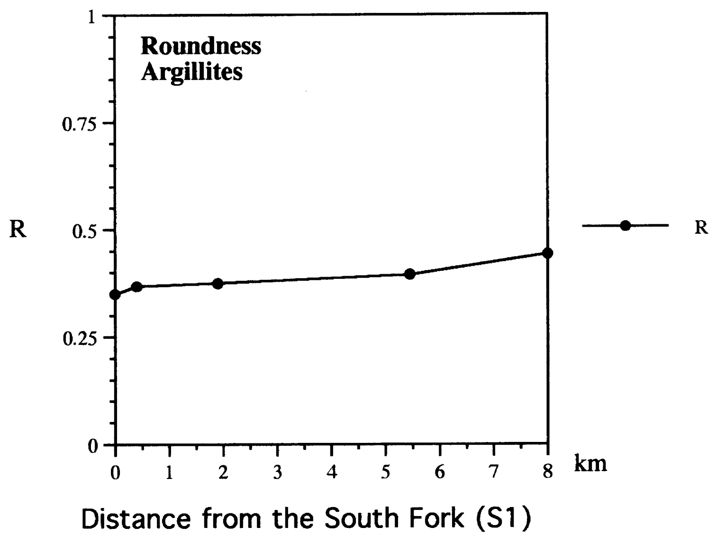


Figure 9. Roundness values for argillites in the 16 – 64 mm fractions of samples S1 – S5. These values increase only minimally over a distance of 7970 m

Results

The values for sphericity derived from the photo-sieved samples show no differences either with respect to the variously aged fan surfaces, or with location on these surfaces. Similarly, samples from the main channel show no changes with distance from the apex. It seems that neither abrasion nor selection cause any significant change during sediment transport, and that sphericity is inherited from the source area.

Roundness values in the main channel increase from 0·36 R to 0·42 R for argillites (Figure 9), and from 0·35 R to 0·38 R for the harder quartzites, where 0·0 R refers to a complete lack of rounding, and 1·0 R refers to a perfectly rounded ellipsoid (see Diepenbroek *et al*., 1992). Different projection planes show slightly different results, but the trend is the same. We therefore used only the LI (long and intermediate axes) projection,

following common practice. Results derived from this projection indicate only a slight increase in roundness values along the incised channel, similar to results obtained from short, steep rivers in Calabria (Ibbeken and Schleyer, 1991). These results indicate transport mechanisms that do not cause clast abrasion. Roundness and sphericity of the analysed clasts on Hanaupah Fan display little variation, i.e. the fan shows a remarkable homogeneity over the entire 30 km^2 area.

CLAST ORIENTATION

We determined clast orientation for the 139 photo-sieved samples. Orientation is derived from the phase shift of the second frequency of the Fourier spectrum (Diepenbroek *et al*., 1992) and is plotted with respect to transport direction. In this way, all measured orientations can be represented as deviations from transport direction. We defined 'transport direction' as a line connecting the sample site with the apex of the fan, or the direction of greatest surface slope. In order to avoid ambiguities, we only measured clasts with axial ratios >1·5 (length of the largest axis is at least 50 per cent greater than length of the intermediate axis).

Results of these orientation measurements (Figure 10) show the following. First, the distribution of clast orientation in the main channel is clearly bimodal, i.e. the long axes of clasts are either parallel or at right angles to transport direction. This bimodal orientation must be a product of the depositional processes. Because this bimodality is a primary character of the sediment in the incised channel, a similar type of orientation should obtain on the older fan surfaces if those surfaces developed under similar conditions, unaffected by post-depositional changes. Clearly, this is not the case (Figure 10). Bimodality of orientation disappears with increasing age of the surfaces, and orientation becomes unimodal, i.e. long clast axes are normal to transport direction on the Q1 surface. This change in modality appears to be significant and systematic, and must be related to post-depositional processes, such as reorientation from recessional debris-flow water flow, or subsequent overland flow (e.g. Blair and McPherson, 1994). If this change in orientation pattern occurs on other fans as well, then perhaps these relationships provide a useful relative-age dating method.

DISCUSSION AND CONCLUSIONS

Our results demonstrate that, despite different ages, the Q1, Q2 and Q3 surfaces of Hanaupah Fan do not differ in their grain-size distributions, but that they are better sorted than the deposits in the incised channel because of the absence of sand and mud. In addition, there are no size differences between the proximal and distal parts of individual surfaces. Furthermore, neither the grain-size distributions in the incised channel, nor the maximal sizes of individual boulders on the fan surfaces, display any significant trend. Only the Lake Manly shoreline deposits are different by being much better sorted, owing to their different depositional origin.

Sphericity and roundness of surface clasts are essentially identical across the fan. The same holds true for clast composition of samples from the incised channel: there is no relative enrichment of resistant lithologies with distance from the apex. Overall, the only significant trend is in the orientation of clasts. Orientation appears to evolve from bimodal in the incised channel to unimodal on the oldest fan surface. Debris flows commonly orient clasts with their long axes slope-parallel along the sides of lobes or levees, and in a slope-normal orientation at lobe snouts (Terence C. Blair, pers. comm., 1997). Subsequent overland flow will reorient clasts so that their long axes become increasingly slope-normal. This interpretation is consistent with a winnowed origin of the fan surface. Other surface processes may contribute to this change in orientation. All in all, clast parameters on Hanaupah Fan are highly homogenous. Depositional episodes seem to produce near-uniform sedimentary units over a large surface area of a still-active segment, followed by modification by secondary overland flow (see Blair and McPherson, 1994) and other surface processes which continue after a segment has become abandoned. Most of these post-depositional changes must occur reasonably rapidly, geologically speaking, since we do not see any significant differences between the variously aged fan surfaces. However, the rate of change in the orientation of surface clasts is much slower, since here we do see a significant differentiation according to age. Even if the exact age assignments of Hanaupah Fan surfaces are still uncertain, the relative age differentiation is not (see Dorn *et al*., 1987b; Wells and McFadden, 1987). Whether or not the postulated, large depositional episodes are concentrated during certain climatic intervals, must be resolved by other studies (e.g. Blair, 1987; Wells *et al*., 1987; Dorn, 1988; Reheis *et al*., 1996).

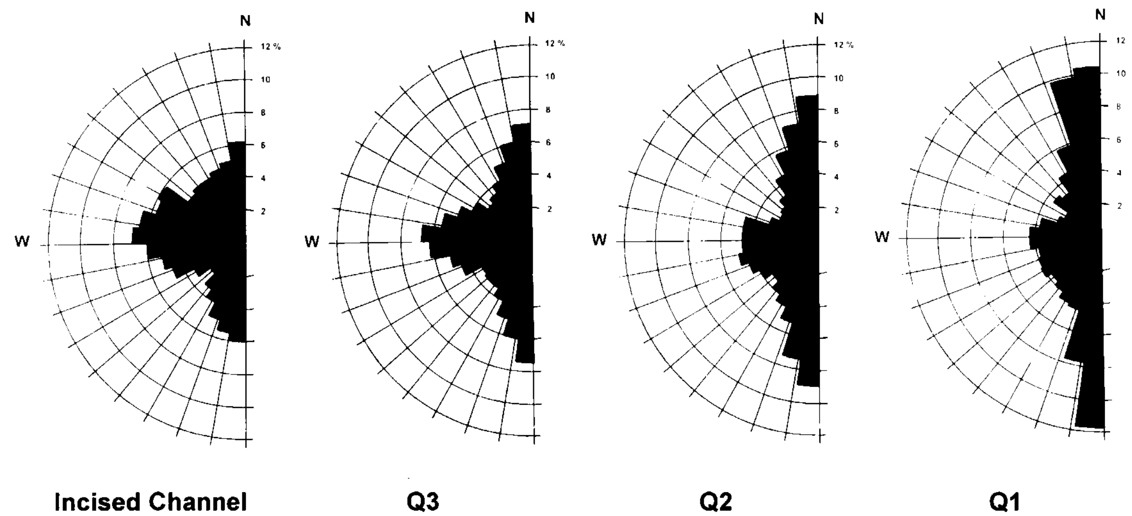


Figure 10. Clast orientation in the incised channel and on Q1, Q2 and Q3 surfaces. There is a distinct progression from bimodal distribution in the incised channel (one mode normal, one mode parallel to transport direction) to unimodal on the oldest Q1 surface (only one mode normal to transport direction)

ACKNOWLEDGEMENTS

This work was carried out as part of a joint project between the Freie Universität Berlin and California State University, Hayward. We thank the DFG for financial support (Grant Nr. Ib 4/17-1,2), and Cal State Hayward for support through a RSCA Grant, School of Science Research Grant, and the use of field vehicles. We thank all participants in the field work, and our colleagues for discussions. We are indebted to Michael Church and Terry Blair for thorough reviews.

REFERENCES

Albee, A. L., Labotka, T. C., Lanphere, M. A. and McDowell, S. D. 1981. Geologic map of the Telescope Peak Quadrangle, California. US Geological Survey Geologic Quadrangle Map GQ-1532.

Blair, T. C. 1987. 'Sedimentary processes, vertical stratification sequences and geomorphology of the Roaring River Alluvial Fan, Rocky Mountain National Park, Colorado', *Journal of Sedimentary Petrology*, **57**, 1–18.

Blair, T. C. and McPherson, J. G. 1994. 'Alluvial fan processes and forms', in Abrahams, A. D. and Parsons, A. J. (Eds), *Geomorphology of Desert Environments*, Chapman and Hall, London, 354–402.

Denny, C. S. 1965. *Alluvial fans of the Death Valley region, California and Nevada*, US Geological Survey Professional Paper **466**, 62 pp.

Diepenbroek, M., Bartholoma, A. and Ibbeken, H. 1992. 'How round is round? A new approach to the topic ''roundness'' by Fourier grain shape analysis', *Sedimentology*, **39**, 411–422.

Dorn, R. I. 1988. 'A rock varnish interpretation of alluvial-fan development in Death Valley, California', *National Geographic Research*, **4**, 56–73.

Dorn, R. I. 1989. 'Cation-ratio dating of rock varnish: a geographic perspective', *Progress in Physical Geography*, **13**, 559–596.

Dorn, R. I., DeNiro, M. J. and Ajie, H. O. 1987a. 'Isotopic evidence for climatic influence on alluvial-fan development in Death Valley, California', *Geology*, **15**, 108–110.

Dorn, R. I., DeNiro, M. J. and Ajie, H. O. 1987b. 'Comment and Reply on ''Isotopic evidence for climatic influence on alluvial-fan development in Death Valley, California'' ', *Geology*, **15**, 1179–1180.

Dorn, R. I., Jull, A. J. T., Donahue, D. J., Linick, T. W. and Toolin, L. J. 1989. 'Accelerator mass spectrometry radiocarbon dating of rock varnish', *Geological Society of America Bulletin*, **101**, 1363–1372.

Folk, R. L. and Ward, W. C. 1957. 'Brazos River bar: A study in the significance of grain size parameters', *Journal of Sedimentary Petrology*, **27**, 3–26.

Hooke, R. LeB. 1972. 'Geomorphic evidence for late-Wisconsin and Holocene tectonic deformation, Death Valley, California', *Geological Society of America Bulletin*, **83**, 2073–2098.

Hooke, R. LeB. and Dorn, R. I. 1992. 'Segmentation of alluvial fans in Death Valley, California: New insights from surface exposure dating and laboratory modelling', *Earth Surface Processes and Landforms*, **17**, 557–574.

Ibbeken, H. and Schleyer, R. 1986. 'Photo-sieving: A method for grain-size analysis of coarse-grained, unconsolidated bedding surfaces', *Earth Surface Processes and Landforms*, **11**, 59–77.

Labotka, T. C., Albee, A. L., Lanphere, M. A. and McDowell, S. D. 1980. 'Stratigraphy, structure, and metamorphism in the central Panamint Mountains (Telescope Peak quadrangle), Death Valley area, California', *Geological Society of America Bulletin*, **91**, 125–129, 843–933.
Lustig, L. K. 1965. *Clastic sedimentation in Deep Springs Valley, California*, USGS Professional Paper **352-F**, 131–192.
Reheis, M. C., Slate, J. L., Throckmorton, C. K., McGeehin, J. P., Sarna-Wojcicki, A. M. and Dengler, L. 1996. 'Late Quaternary sedimentation on the Leidy Creek fan, Nevada–California: geomorphic responses to climate change', *Basin Research*, **8**, 279–299.
Wells, S. G. and McFadden, L. D. 1987. 'Comment and Reply on ''Isotopic evidence for climatic influence on alluvial-fan development in Death Valley, California''', *Geology*, **15**, 1178.
Wells, S. G., McFadden, L. L. and Dohrenwend, J. C. 1987. 'Influence of Late Quaternary climatic changes on geomorphic and pedogenic processes on a desert piedmont, eastern Mojave Desert, California', *Quaternary Research*, **27**, 130–146.

